

# Molecular Cloud Turbulence and Star Formation

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We review the properties of turbulent molecular clouds (MCs), focusing on the physical processes that influence star formation (SF). MC formation appears to occur during large-scale compression of the diffuse ISM driven by supernovae, magnetorotational instability, or gravitational instability in galactic disks of stars and gas. The compressions generate turbulence that can accelerate molecule production and produce the observed morphology. We then review the properties of MC turbulence, including density enhancements observed as clumps and cores, magnetic field structure, driving scales, the relation to observed scaling relations, and the interaction with gas thermodynamics. We argue that MC cores are dynamical, not quasistatic, objects with relatively short lifetimes not exceeding a few megayears. We review their morphology, magnetic fields, density and velocity profiles, and virial budget. Next, we discuss how MC turbulence controls SF. On global scales turbulence prevents monolithic collapse of the clouds; on small scales it promotes local collapse. We discuss its effects on the SF efficiency, and critically examine the possible relation between the clump mass distribution and the initial mass function, and then turn to the redistribution of angular momentum during collapse and how it determines the multiplicity of stellar systems. Finally, we discuss the importance of dynamical interactions between protostars in dense clusters, and the effect of the ionization and winds from those protostars on the surrounding cloud. We conclude that the interaction of self-gravity and turbulence controls MC formation and behavior, as well as the core and star formation processes within them.

## 1. INTRODUCTION

Star formation occurs within molecular clouds (MCs). These exhibit supersonic linewidths, which are interpreted as evidence for supersonic turbulence (Zuckerman and Evans, 1974). Early studies considered this property mainly as a mechanism of MC support against gravity. In more recent years, however, it has been realized that turbulence is a fundamental ingredient of MCs, determining properties such as their morphology, lifetimes, rate of star formation, etc.

Turbulence is a multiscale phenomenon in which kinetic energy cascades from large scales to small scales. The bulk of the specific kinetic energy remains at large scales. Turbulence appears to be dynamically important from scales of whole MCs down to cores (e.g., Larson, 1981; Ballesteros-Paredes et al., 1999a; Mac Low and Klessen, 2004). Thus, early microturbulent descriptions postulating that turbulence *only* acts on small scales did not capture major effects at large scales such as cloud and core formation by the turbulence.

Turbulence in the warm diffuse interstellar medium (ISM) is transonic, with both the sound speed and the non-thermal motions being  $\sim 10 \text{ km s}^{-1}$  (Kulkarni and Heiles, 1987; Heiles and Troland, 2003), while within MCs it is highly supersonic, with Mach numbers  $\mathcal{M} \approx 5\text{--}20$  (Zuckerman and Palmer, 1974). Both media are highly compressible. Hypersonic velocity fluctuations in the roughly isothermal molecular gas produce large density enhancements at shocks. The velocity fluctuations in the warm diffuse medium, despite being only transonic, can still drive large density enhancements because they can push the medium into a thermally unstable regime in which the gas cools rapidly into a cold, dense regime (Hennebelle and P  rault, 1999). In general, the atomic gas responds close to isobarically to dynamic compressions for densities  $0.5 \lesssim n/\text{cm}^{-3} \lesssim 40$  (Gazol et al., 2005). We argue in this review that MCs form from dynamically evolving, high-density features in the diffuse ISM. Similarly, their internal substructure of clumps and cores are also transient density enhancements continually changing their shape and even

the material contained in the turbulent flow, behaving as something between discrete objects and waves (Vázquez-Semadeni *et al.*, 1996). Because of their higher density, some clumps and cores become gravitationally unstable and collapse to form stars.

We here discuss the main advances in our understanding of the turbulent properties of MCs and their implications for star formation since the reviews by Vázquez-Semadeni *et al.* (2000) and Mac Low and Klessen (2004), proceeding from large (giant MCs) to small (core) scales.

## 2. MOLECULAR CLOUD FORMATION

The questions of how MCs form and what determines their physical properties have remained unanswered until recently (e.g., Elmegreen, 1991; Blitz and Williams, 1999). Giant molecular clouds (GMCs) have gravitational energy far exceeding their thermal energy (Zuckerman and Palmer, 1974), although comparable to their turbulent (Larson, 1981) and magnetic energies (Myers and Goodman, 1988; Crutcher, 1999; Bourke *et al.*, 2001; Crutcher *et al.*, 2004). This near equipartition of energies has traditionally been interpreted as indicative of approximate virial equilibrium, and thus of general stability and longevity of the clouds (e.g., McKee *et al.*, 1993; Blitz and Williams, 1999). In this picture, the fact that MCs have thermal pressures exceeding that of the general ISM by roughly one order of magnitude (e.g., Blitz and Williams, 1999) was interpreted as a consequence of their being strongly self-gravitating (e.g., McKee, 1995), while the magnetic and turbulent energies were interpreted as support against gravity. Because of the interpretation that their overpressures were due to self-gravity, MCs could not be incorporated into global ISM models based on thermal pressure equilibrium, such as those by Field *et al.* (1969); McKee and Ostriker (1977); Wolfire *et al.* (1995).

Recent work suggests instead that MCs are likely to be *transient*, dynamically evolving features produced by compressive motions of either gravitational or turbulent origin, or some combination thereof. In what follows we first discuss these two formation mechanisms, and then discuss how they can give rise to the observed physical and chemical properties of MCs.

### 2.1. Formation mechanisms

Large-scale gravitational instability in the combined medium of the collisionless stars and the collisional gas appears likely to be the main driver of GMC formation in galaxies. In the Milky Way, MCs, and particularly GMCs, are observed to be concentrated towards the spiral arms (Lee *et al.*, 2001; Blitz and Rosolowsky, 2005; Stark and Lee, 2005), which are the first manifestation of gravitational instability in the combined medium. We refer to the instability parameter for stars and gas combined (Rafikov, 2001) as the Toomre parameter for stars and gas  $Q_{sg}$ . As  $Q_{sg}$  drops below unity, gravitational instability drives spiral density waves (Lin and Shu, 1964; Lin *et al.*, 1969).

High-resolution numerical simulations of the process then show the appearance of regions of local gravitational collapse in the arms, with the timescale for collapse depending exponentially on the value of  $Q_{sg}$  (Li *et al.*, 2005). In more strongly gravitationally unstable regions towards the centers of galaxies, collapse occurs more generally, with molecular gas dominating over atomic gas, as observed by Wong and Blitz (2002).

The multi-kiloparsec scale of spiral arms driven by gravitational instability suggests that this mechanism should preferentially form GMCs, consistent with the fact that GMCs are almost exclusively confined to spiral arms in our galaxy (Stark and Lee, 2005). Also, stronger gravitational instability causes collapse to occur closer to the disk mid-plane, producing a smaller scale height for GMCs (Li *et al.*, 2005), as observed by Dalcanton *et al.* (2004) and Stark and Lee (2005). In gas-poor galaxies like our own, the self-gravity of the gas in the unperturbed state is negligible with respect to that of the stars, so this mechanism reduces to the standard scenario of the gas falling into the potential well of the stellar spiral and shocking there (Roberts, 1969), with its own self-gravity only becoming important as the gas is shocked and cooled (Section 2.2).

A second mechanism of MC formation operating at somewhat smaller scales (tens to hundreds of pc) is the ram pressure from supersonic flows, which can be produced by a number of different sources. Supernova explosions drive blast waves and superbubbles into the ISM. Compression and gravitational collapse can occur in discrete superbubble shells (McCray and Kafatos, 1987). The ensemble of supernova remnants, superbubbles and expanding HII regions in the ISM drives a turbulent flow (Vázquez-Semadeni *et al.*, 1995; Passot *et al.*, 1995; Rosen and Bregman, 1995; Korpi *et al.*, 1999; Gazol-Patiño and Passot, 1999; de Avillez, 2000; Avila-Reese and Vázquez-Semadeni, 2001; Slyz *et al.*, 2005; Mac Low *et al.*, 2005; Dib *et al.*, 2006; Joung and Mac Low, 2006). Finally, the magnetorotational instability (Balbus and Hawley, 1998) in galaxies can drive turbulence with velocity dispersion close to that of supernova-driven turbulence even in regions far from recent star formation (Sellwood and Balbus, 1999; Kim *et al.*, 2003; Dziourkevitch *et al.*, 2004; Piontek and Ostriker, 2005). Both of these sources of turbulence drive flows with velocity dispersion  $\sim 10 \text{ km s}^{-1}$ , similar to that observed (Kulkarni and Heiles, 1987; Dickey and Lockman, 1990; Heiles and Troland, 2003). The high- $\mathcal{M}$  tail of the shock distribution in the warm medium involved in this turbulent flow can drive MC formation.

Small-scale, scattered, ram-pressure compressions in a globally gravitationally stable medium can produce clouds that are globally supported against collapse, but that still undergo local collapse in their densest substructures. These events involve a small fraction of the total cloud mass and are characterized by a shorter free-fall time than that of the parent cloud because of the enhanced local density (Sasao, 1973; Elmegreen, 1993; Padoan, 1995; Vázquez-Semadeni *et al.*, 1996; Ballesteros-Paredes *et al.*, 1999b;a; Klessen

*et al.*, 2000; *Heitsch et al.*, 2001a; *Vázquez-Semadeni et al.*, 2003; 2005b; *Li and Nakamura*, 2004; *Nakamura and Li*, 2005; *Clark et al.*, 2005). Large-scale gravitational contraction, on the other hand, can produce strongly bound GMCs in which gravitational collapse proceeds efficiently. In either case, mass that does not collapse sees its density reduced, and may possibly remain unbound throughout the evolution (*Bonnell et al.*, 2006). The duration of the entire gas accumulation process to form a GMC by either kind of compressions may be  $\sim 10\text{--}20$  Myr, with the duration of the mainly *molecular* phase probably constituting only the last 3–5 Myr (*Ballesteros-Paredes et al.*, 1999b; *Hartmann*, 2001; *Hartmann et al.*, 2001; *Hartmann*, 2003).

Thus, GMCs and smaller MCs may represent two distinct populations: One formed by the large-scale gravitational instability in the spiral arms, and concentrated toward the midplane because of the extra gravity in the arms; the other, formed by more scattered turbulent compression events, probably driven by supernovae, and distributed similarly to the turbulent atomic gas.

## 2.2. Origin of Molecular Cloud Properties

Large-scale compressions can account for the physical and chemical conditions characteristic of MCs, whether the compression comes from gravity or ram pressure. *Hartmann et al.* (2001) estimated that the column density thresholds for becoming self-gravitating, molecular, and magnetically supercritical are very similar (see also *Franco and Cox*, 1986),  $N \sim 1.5 \times 10^{21} (P_e/k)_4^{1/2} \text{ cm}^{-2}$ , where  $(P_e/k)_4$  is the pressure external to the cloud in units of  $10^4 \text{ K cm}^{-3}$ .

MCs are observed to be magnetically critical (*Crutcher et al.*, 2003), yet the diffuse atomic ISM is reported to be subcritical (e.g., *Crutcher et al.*, 2003; *Heiles and Troland*, 2005), apparently violating mass-to-magnetic flux conservation. However, the formation of a GMC of  $10^6 M_\odot$  out of diffuse gas at  $1 \text{ cm}^{-3}$  requires accumulation lengths  $\sim 400$  pc, a scale over which the diffuse ISM is magnetically critical (*Hartmann et al.*, 2001). Thus, reports of magnetic subcriticality need to be accompanied by an estimate of the applicable length scale.

Large-scale compressions also appear capable of producing the observed internal turbulence in MCs. *Vishniac* (1994) showed analytically that bending modes in isothermal shock-bounded layers are *nonlinearly* unstable. This analysis has been confirmed numerically (*Hunter et al.*, 1986; *Stevens et al.*, 1992; *Blondin and Marks*, 1996; *Walder and Folini*, 1998; 2000), demonstrating that shock-bounded, radiatively cooled layers can become unstable and develop turbulence. Detailed models of the compression of the diffuse ISM show that the compressed post-shock gas undergoes both thermal and dynamical instability, fragmenting into cold, dense clumps with clump-to-clump velocity dispersions of a few kilometers per second, supersonic with respect to their internal sound speeds (*Koyama and Inutsuka*, 2002; *Inutsuka and Koyama*, 2004; *Audit and*

*Hennebelle*, 2005; *Heitsch et al.*, 2005; *Vázquez-Semadeni et al.*, 2006). *Inutsuka and Koyama* (2004) included magnetic fields, with similar results. *Vázquez-Semadeni et al.* (2006) further showed that gas with MC-like densities occurs in regions overpressured by dynamic compression to factors of as much as 5 above the mean thermal pressure (see Fig. 1). These regions are the density peaks in a turbulent flow, rather than ballistic objects in a diffuse substrate. Very mildly supersonic compressions can form thin, cold atomic sheets like those observed by *Heiles and Troland* (2003) rather than turbulent, thick objects like MCs. Depending on the inflow Mach number, turbulence can take 5–100 Myr to develop.

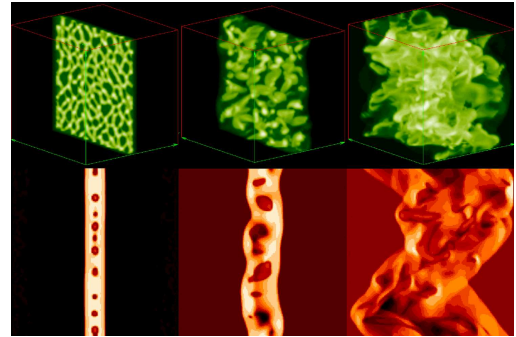


Fig. 1.— *Top*: Projections of the density field in a simulation of MC formation by the collision of convergent streams, each at a Mach number  $\mathcal{M} = 2.4$ . From left to right, times  $t = 2, 4$  and  $7.33$  Myr are shown, illustrating how the collision first forms a thin sheet that then fragments, becomes turbulent, and thickens, until it becomes a fully three-dimensional cloud. *Bottom*: Cross sections through the pressure field at the  $xy$  plane at half the  $z$  extension of the simulation. The color code ranges from  $P/k = 525$  (black) to  $7000 \text{ K cm}^{-3}$  (white). (From *Vázquez-Semadeni et al.*, 2006).

A crucial question is whether molecules can form on the short timescales (3–5 Myr) implied by the ages of the stellar populations in nearby star-forming regions (*Ballesteros-Paredes et al.*, 1999a; *Hartmann*, 2001; *Hartmann et al.*, 2001).  $\text{H}_2$  molecule formation on grains occurs on timescales  $t_f = 10^9 \text{ yr}/n$  (*Hollenbach and Salpeter*, 1971; *Jura*, 1975). *Pavlovski et al.* (2002) showed that, in a turbulent flow,  $\text{H}_2$  formation proceeds fastest in the highest density enhancements, yet the bulk of the mass passes through those enhancements quickly. *Glover and Mac Low* (2005) confirm that this mechanism produces widespread molecular gas at average densities of order  $10^2 \text{ cm}^{-3}$  in compressed, turbulent regions. This may explain recent observations of diffuse ( $n_{\text{H}} \leq 30 \text{ cm}^{-3}$ ) cirrus clouds that exhibit significant fractions of  $\text{H}_2$  ( $\sim 1\%\text{--}30\%$  *Gillmon and Shull*, 2006). Rapid  $\text{H}_2$  formation suggests that a more relevant MC formation timescale is that required to accumulate a sufficient column density for extinction to allow CO formation. Starting from H I with  $n \sim 1 \text{ cm}^{-3}$ , and  $\delta v \sim 10 \text{ km/sec}$ , this is  $\sim 10\text{--}20$  Myr (*Bergin et al.*, 2004).

In the scenario we have described, MCs are generally not in equilibrium, but rather evolving secularly. They start as

atomic gas that is compressed, increasing its mean density. The atomic gas may or may not be initially self-gravitating, but in either case the compression causes the gas to cool via thermal instability and to develop turbulence via dynamical instabilities. Thermal instability and turbulence promote fragmentation and, even though the self-gravity of the cloud as a whole is increased due to cooling and the compression, the free-fall time in the fragments is shorter, so collapse proceeds locally, preventing monolithic collapse of the cloud and thus reducing the star formation efficiency (Section 5.1). The near equipartition between their gravitational, magnetic and turbulent kinetic energies is not necessarily a condition of equilibrium (Maloney, 1990; Vázquez-Semadeni et al., 1995; Ballesteros-Paredes and Vázquez-Semadeni, 1997; Ballesteros-Paredes et al., 1999a), and instead may simply indicate that self-gravity has become important either due to large-scale gravitational instability or local cooling.

### 3. PROPERTIES OF MOLECULAR CLOUD TURBULENCE

In a turbulent flow with velocity power spectrum having negative slope, the typical velocity difference between two points decreases as their separation decreases. Current observations give  $\Delta v \approx 1 \text{ km s}^{-1} (R/[1 \text{ pc}])^\beta$  with  $\beta \simeq 0.38\text{--}0.5$  (e.g., Larson, 1981; Blitz, 1993; Heyer and Brunt, 2004). This scaling law implies that the typical velocity difference across separations  $\ell > \lambda_s \sim 0.05 \text{ pc}$  is supersonic, while it is subsonic for  $\ell < \lambda_s$ , where we define  $\lambda_s$  as the sonic scale. Note that dropping to subsonic velocity is unrelated to reaching the dissipation scale of the turbulence, though there may be a change in slope of the velocity power spectrum at  $\lambda_s$ .

The roughly isothermal supersonic turbulence in MCs at scales  $\ell > \lambda_s$  produces density enhancements that appear to constitute the clumps and cores of MCs (von Weizsäcker, 1951; Sasao, 1973; Elmegreen, 1993; Padoan, 1995; Ballesteros-Paredes et al., 1999a), since the density jump associated with isothermal shocks is  $\sim \mathcal{M}^2$ . Conversely, the subsonic turbulence at  $\ell < \lambda_s$  within cores does not drive further fragmentation, and is less important than thermal pressure in resisting self-gravity (Padoan, 1995; Vázquez-Semadeni et al., 2003).

#### 3.1. Density Fluctuations and Magnetic Fields

The typical amplitudes and sizes of density fluctuations driven by supersonic turbulence determine if they will become gravitationally unstable and collapse to form one or more stars. One of the simplest statistical indicators is the density probability distribution function (PDF). For nearly isothermal flows subject to random accelerations, the density PDF develops a log-normal shape (Vázquez-Semadeni, 1994; Padoan et al., 1997a; Passot and Vázquez-Semadeni, 1998; Klessen, 2000). This is the expected shape if the density fluctuations are built by successive passages of shock waves at any given location and the jump amplitude is inde-

pendent of the local density (Passot and Vázquez-Semadeni, 1998; Nordlund and Padoan, 1999). Numerical studies in three dimensions suggest that the standard deviation of the logarithm of the density fluctuations  $\sigma_{\log \rho}$  scales with the logarithm of the Mach number (Padoan et al., 1997a; Mac Low et al., 2005).

Similar features appear to persist in the isothermal, ideal MHD case (Ostriker et al., 1999; 2001; Falle and Hartquist, 2002), with the presence of the field not significantly affecting the shape of the density PDF except for particular angles between the field and the direction of the MHD wave propagation (Passot and Vázquez-Semadeni, 2003). In general,  $\sigma_{\log \rho}$  tends to decrease with increasing field strength  $B$ , although it exhibits slight deviations from monotonicity. Some studies find that intermediate values of  $B$  inhibit the production of large density fluctuations better than larger values (Passot et al., 1995; Ostriker et al., 2001; Ballesteros-Paredes and Mac Low, 2002; Vázquez-Semadeni et al., 2005a). This may be due to a more isotropic behavior of the magnetic pressure at intermediate values of  $B$  (see also Heitsch et al., 2001a).

An important observational (Crutcher et al., 2003) and numerical (Padoan and Nordlund, 1999; Ostriker et al., 2001; Passot and Vázquez-Semadeni, 2003) result is that the magnetic field strength appears to be uncorrelated with the density at low-to-moderate densities or strong fields, while a correlation appears at high densities or weak fields. Passot and Vázquez-Semadeni (2003) suggest this occurs because the slow mode dominates for weak fields, while the fast mode dominates for strong fields.

Comparison of observations to numerical models has led Padoan and Nordlund (1999), Padoan et al. (2003) and Padoan et al. (2004a) to strongly argue that MC turbulence is not just supersonic but also super-Alfvénic with respect to the initial mean field. Padoan and Nordlund (1999) notes that such turbulence can easily produce trans- or even sub-Alfvénic cores. Also, at advanced stages, the total magnetic energy including fluctuations in driven turbulence approaches the equipartition value (Padoan et al., 2003), due to turbulent amplification of the magnetic energy (Ostriker et al., 1999; Schekochihin et al., 2002). Observations, on the other hand, are generally interpreted as showing that MC cores are magnetically critical or moderately supercritical and therefore trans- or super-Alfvénic if the turbulence is in equipartition with self-gravity (Bertoldi and McKee 1992; Crutcher 1999; Bourke et al. 2001; Crutcher et al. 2003; see also the chapter by di Francesco et al.). However, the observational determination of the relative importance of the magnetic field strength in MCs depends on their assumed geometry, and the clouds could even be strongly super-critical (Bourke et al., 2001). Unfortunately, the lack of self-gravity, which could substitute for stronger turbulence in the production of denser cores in the simulations by Padoan and coworkers, implies that the evidence in favor of super-Alfvénic MCs remains inconclusive.

### 3.2. Driving and Decay of the Turbulence

Supersonic turbulence should decay in a crossing time of the driving scale (Goldreich and Kwan, 1974; Field, 1978). For a number of years it was thought that magnetic fields might modify this result (Arons and Max, 1975), but it has been numerically confirmed that both hydrodynamical and MHD turbulence decay in less than a free-fall time, whether or not an isothermal equation of state is assumed (Stone et al., 1998; Mac Low et al., 1998; Padoan and Nordlund, 1999; Biskamp and Müller, 2000; Avila-Reese and Vázquez-Semadeni, 2001; Pavlovski et al., 2002). Decay does proceed more slowly if there are order of magnitude imbalances in motions in opposite directions (Maron and Goldreich, 2001; Cho et al., 2002), though this seems unlikely to occur in MCs.

Traditionally, MCs have been thought to have lifetimes much larger than their free-fall times (e.g., Blitz and Shu, 1980). However, recent work suggests that MC lifetimes may be actually comparable or shorter than their free-fall times (Ballesteros-Paredes et al., 1999b; Hartmann et al., 2001; Hartmann, 2003), and that star formation occurs within a single crossing time at all scales (Elmegreen, 2000b). If true, and if clouds are destroyed promptly after star formation has occurred (Fukui et al., 1999; Yamaguchi et al., 2001), this suggests that turbulence is ubiquitously observed simply because it is produced together with the cloud itself (see Section 2.2) and it does not have time to decay afterwards.

Observations of nearby MCs show them to be self-similar up to the largest scales traced by molecules (Mac Low and Ossenkopf, 2000; Ossenkopf et al., 2001; Ossenkopf and Mac Low, 2002; Brunt, 2003; Heyer and Brunt, 2004), suggesting that they are driven from even larger scales (see also Section 4.2). If the turbulent or gravitational compressions that form MCs drive the turbulence, then the driving scale would indeed be larger than the clouds.

### 3.3. Spectra and Scaling Relations

Scaling relations between the mean density and size, and between velocity dispersion and size (Larson, 1981) have been discussed in several reviews (e.g., Vázquez-Semadeni et al., 2000; Mac Low and Klessen, 2004; Elmegreen and Scalo, 2004). In order to avoid repetition, we comment in detail only on the caveats not discussed there.

The Larson relation  $\langle \rho \rangle \sim R^{-1}$  implies a constant column density. However, observations tend to have a limited dynamic range, and thus to select clouds with similar column densities (Kegel, 1989; Scalo, 1990; Schneider and Brooks, 2004), as already noted by Larson himself. Numerical simulations of both the diffuse ISM (Vázquez-Semadeni et al., 1997) and of MCs (Ballesteros-Paredes and Mac Low, 2002) suggest that clouds of lower column density exist. However, when the observational procedure is simulated, then the mean density-size relation appears, showing that it is likely to be an observational artifact.

Elmegreen and Scalo (2004) suggested that the mass-

size relation found in the numerical simulations of Ostriker et al. (2001) supports the reality of the  $\langle \rho \rangle$ - $R$  relation. However, those authors defined their clumps using a procedure inspired by observations, focusing on regions with higher-than-average column density. As in noise-limited observations, this introduces an artificial cutoff in column density, which again produces the appearance of a  $\langle \rho \rangle$ - $R$  relation.

Nevertheless, the fact that the column density threshold for a cloud to become molecular is similar to that for becoming self-gravitating (Franco and Cox, 1986; Hartmann et al., 2001) may truly imply a limited column density range for molecular gas, since clouds of lower column density are not molecular, while clouds with higher column densities collapse quickly. MCs constitute only the tip of the iceberg of the neutral gas distribution.

The  $\Delta v$ - $R$  relation is better established. However, it does not appear to depend on self-gravitation as has often been argued. Rather it appears to be a measurement of the second-order structure function of the turbulence (Elmegreen and Scalo, 2004), which has a close connection with the energy spectrum  $E(k) \propto k^n$ . The relation between the spectral index  $n$  and the exponent in the velocity dispersion-size relation  $\Delta v \propto R^\beta$ , is  $\beta = -(n+1)/2$ . Observationally, the value originally found by Larson (1981),  $\beta \approx 0.38$ , is close to the value expected for incompressible, Kolmogorov turbulence ( $\beta = 1/3$ ,  $n = -5/3$ ). More recent surveys of whole GMCs tend to give values  $\beta \sim 0.5$ – $0.65$  (Blitz, 1993; Mizuno et al., 2001; Heyer and Brunt, 2004), with smaller values arising in low surface brightness regions of clouds (Falgarone et al., 1992,  $\beta \sim 0.4$ ) and massive core surveys (Caselli and Myers, 1995; Plume et al., 1997,  $\beta \sim 0$ – $0.2$ , and very poor correlations). The latter may be affected by intermittency effects, stellar feedback, or strong gravitational contraction. Numerically, simulations of MCs and the diffuse ISM (Vázquez-Semadeni et al., 1997; Ostriker et al., 2001; Ballesteros-Paredes and Mac Low, 2002) generally exhibit very noisy  $\Delta v$ - $R$  relations both in physical and observational projected space, with slopes  $\beta \sim 0.2$ – $0.4$ . The scatter is generally larger at small clump sizes, both in physical space, perhaps because of intermittency, and in projection, probably because of feature superposition along the line of sight.

There is currently no consensus on the spectral index for compressible flows. A value  $n = -2$  ( $\beta = 1/2$ ) is expected for shock-dominated flows (e.g., Elsässer and Schamel, 1976), while Boldyrev (2002) has presented a theoretical model suggesting that  $n \approx -1.74$ , and thus  $\beta \approx 0.37$ . The predictions of this model for the higher-order structure function scalings appear to be confirmed numerically (Boldyrev et al., 2002; Padoan et al., 2004b; Joungh and Mac Low, 2006; de Avillez and Breitschwerdt, 2006). However, the model assumes incompressible Kolmogorov scaling at large scales on the basis of simulations driven with purely solenoidal motions (Boldyrev et al., 2002), which does not appear to agree with the behavior seen by ISM simulations (e.g., de Avillez, 2000; Joungh and Mac Low, 2006).

Numerically, Passot et al. (1995) reported  $n = -2$

in their two-dimensional simulations of magnetized, self-gravitating turbulence in the diffuse ISM. More recently, *Boldyrev et al.* (2002) have reported  $n = -1.74$  in isothermal, non-self-gravitating MHD simulations, while other studies find that  $n$  appears to depend on the rms Mach number of the flow in both magnetic and non-magnetic cases (*Cho and Lazarian, 2003; Ballesteros-Paredes et al., 2006*), approaching  $n = -2$  at high Mach numbers.

### 3.4. Thermodynamic Properties of the Star-Forming Gas

While the atomic gas is tenuous and warm, with densities  $1 < n < 100 \text{ cm}^{-3}$  and temperatures  $100 \text{ K} < T < 5000 \text{ K}$ , MCs have  $10^2 < n < 10^3 \text{ cm}^{-3}$ , and locally  $n > 10^6 \text{ cm}^{-3}$  in dense cores. The kinetic temperature inferred from molecular line ratios is typically about 10 K for dark, quiescent clouds and dense cores, but can reach 50–100 K in regions heated by UV radiation from high-mass stars (*Kurtz et al., 2000*).

MC2 temperatures are determined by the balance between heating and cooling, which in turn both depend on the chemistry and dust content. Early studies predicted that the equilibrium temperatures in MC cores should be 10–20 K, tending to be lower at the higher densities (e.g., *Hayashi, 1966; Larson, 1969; 1973; Goldsmith and Langer, 1978*). Observations generally agree with these values (*Jijina et al., 1999*), prompting most theoretical and numerical star-formation studies to adopt a simple isothermal description, with  $T \sim 10 \text{ K}$ .

In reality, however, the temperature varies by factors of two or three above and below the assumed constant value (*Goldsmith, 2001; Larson, 2005*). This variation can be described by an effective equation of state (EOS) derived from detailed balance between heating and cooling when cooling is fast (*Vázquez-Semadeni et al., 1996; Passot and Vázquez-Semadeni, 1998; Scalo et al., 1998; Spaans and Silk, 2000; Li et al., 2003; Spaans and Silk, 2005*). This EOS can often be approximated by a polytropic law of the form  $P \propto \rho^\gamma$ , where  $\gamma$  is a parameter. For molecular clouds, there are three main regimes for which different polytropic EOS can be defined. (a) For  $n \lesssim 2.5 \times 10^5 \text{ cm}^{-3}$ , MCs are externally heated by cosmic rays or photoelectric heating, and cooled mainly through the emission of molecular (e.g., CO, H<sub>2</sub>O) or atomic (C II, O, etc.) lines, depending on ionization level and chemical composition (e.g., *Genzel, 1991*). The strong dependence of the cooling rate on density yields an equilibrium temperature that decreases with increasing density. In this regime, the EOS can be approximated by a polytrope with  $\gamma = 0.75$  (*Koyama and Inutsuka, 2000*). Small, dense cores indeed are observed to have  $T \sim 8.5 \text{ K}$  at a density  $n \sim 10^5 \text{ cm}^{-3}$  (*Evans, 1999*). (b) At  $n > 10^6 \text{ cm}^{-3}$ , the gas becomes thermally coupled to dust grains, which then control the temperature by their far-infrared thermal emission. In this regime, the effective polytropic index is found to be  $1 < \gamma < 1.075$ . (*Scalo et al., 1998; Spaans and Silk, 2000; Larson, 2005*).

The temperature is predicted to reach a minimum of 5 K (*Larson, 2005*). Such cold gas is difficult to observe, but observations have been interpreted to suggest central temperatures between 6 K and 10 K for the densest observed prestellar cores. (c) Finally, at  $n > 10^{11} \text{ cm}^{-3}$ , the dust opacity increases, causing the temperature to rise rapidly. This results in an opacity limit to fragmentation that is somewhat below  $0.01 M_\odot$  (*Low and Lynden-Bell, 1976; Masunaga and Inutsuka, 2000*). The transition from  $\gamma < 1$  to  $\gamma \gtrsim 1$  in molecular gas may determine the characteristic stellar mass resulting from gravoturbulent fragmentation (Section 5.2).

## 4. PROPERTIES OF MOLECULAR CLOUD CORES

### 4.1. Dynamical Evolution

**4.1.1. Dynamic or Hydrostatic Cores?** The first successful models of MCs and their cores used hydrostatic equilibrium configurations as the starting point (e.g., *de Jong et al. 1980; Shu et al. 1987; Mouschovias 1991*; see also Section 5.1). However, supersonic turbulence generates the initial density enhancements from which cores develop (e.g., *Sasao, 1973; Passot et al., 1988; Vázquez-Semadeni, 1994; Padoan et al., 1997b; Passot and Vázquez-Semadeni, 1998; Padoan and Nordlund, 1999; Klessen et al., 2000; Heitsch et al., 2001a; Padoan et al., 2001b; Falle and Hartquist, 2002; Passot and Vázquez-Semadeni, 2003; Ballesteros-Paredes et al., 2003; Hartquist et al., 2003; Klessen et al., 2005; Kim and Ryu, 2005; Beresnyak et al., 2005*). Therefore, they do not necessarily approach hydrostatic equilibrium at any point in their evolution (*Ballesteros-Paredes et al., 1999a*). For the dynamically-formed cores to settle into equilibrium configurations, it is necessary that the equilibrium be *stable*. In this subsection we discuss the conditions necessary for the production of stable self-gravitating equilibria, and whether they are likely to be satisfied in MCs.

Known hydrostatic stable equilibria in non-magnetic, self-gravitating media require confinement by an external pressure to prevent expansion (*Bertoldi and McKee, 1992; Hartmann, 1998; Hartmann et al., 2001; Vázquez-Semadeni et al., 2005b*). The most common assumption is a discontinuous phase transition to a warm, tenuous phase that provides pressure without adding weight (i.e., mass) beyond the core's boundary. The requirement of a confining medium implies that the medium must be two-phase, as in the model of *Field et al. (1969)* for the diffuse ISM. Turbulent pressure is probably not a suitable confining agent because it is large-scale, transient, and anisotropic, thus being more likely to cause distortion than confinement of the cores (*Ballesteros-Paredes et al., 1999a; Klessen et al., 2005*).

Bonnor-Ebert spheres are stable for a ratio of central to external density  $< 14$ . Unstable equilibrium solutions exist that dispense with the confining medium by pushing the boundaries to infinity, with vanishing density there. Other, non-spherical, equilibrium solutions exist (e.g., *Curry, 2000*) that do not require an external confining medium, although their stability remains an open question. A suf-

ficiently large pressure increase, such as might occur in a turbulent flow, can drive a stable, equilibrium object unstable.

For mass-to-flux ratios below a critical value, the equations of ideal MHD without ambipolar diffusion (AD) predict unconditionally stable equilibrium solutions, in the sense that no amount of external compression can cause collapse (Shu *et al.*, 1987). However, these configurations still require a confining thermal or magnetic pressure, applied at the boundaries parallel to the mean field, to prevent expansion in the perpendicular direction (Nakano, 1998; Hartmann *et al.*, 2001). Treatments avoiding such a confining medium (e.g., Lizano and Shu, 1989) have used periodic boundary conditions, in which the pressure from the neighboring boxes effectively confines the system. When boundary conditions do not restrict the cores to remain subcritical, as in globally supercritical simulations, subcritical cores do not appear (Li *et al.*, 2004; Vázquez-Semadeni *et al.*, 2005b).

Thus it appears that the boundary conditions of the cores determine whether they can find stable equilibria. Some specific key questions are (a) whether MC interiors can be considered two-phase media; (b) whether the clouds can really be considered magnetically subcritical when the masses of their atomic envelopes are taken into account (cf. Section 2), and (c) whether the magnetic field inside the clouds is strong and uniform enough to prevent expansion of the field lines at the cores. If any of these questions is answered in the positive, the possibility of nearly hydrostatic cores cannot be ruled out. At this point, they do not appear likely to dominate MCs, though.

**4.1.2. Core lifetimes.** Core lifetimes are determined using either chemical or statistical methods. Statistical studies use the observed number ratio of starless to stellar cores in surveys  $n_{\text{sl}}/n_{\text{s}}$  (Beichman *et al.* 1986; Ward-Thompson *et al.* 1994; Lee and Myers 1999; Jijina *et al.* 1999; Jessop and Ward-Thompson 2000; see also the chapter by di Francesco *et al.*), as a measure of the time spent by a core in the pre- and protostellar stages, respectively. This method gives estimates of prestellar lifetimes  $\tau$  of a few hundred thousand to a few million years. Although Jessop and Ward-Thompson (2000) report  $6 \leq \tau \leq 17$  Myr, they likely overestimate the number of starless cores because to find central stars they rely on IRAS measurements of relatively distant clouds ( $\sim 350$  pc), and so probably miss many of the lower mass stars. This is a general problem of the statistical method (Jørgensen *et al.*, 2005). Indeed, Spitzer observations have begun to reveal embedded sources in cores previously thought to be starless (e.g., Young *et al.*, 2004). Another problem is that if not all present-day starless cores eventually form stars, then the ratio  $n_{\text{sl}}/n_{\text{s}}$  overestimates the lifetime ratio. Numerical simulations of isothermal turbulent MCs indeed show that a significant fraction of the cores (dependent on the exact criterion used to define them) end up re-expanding rather than collapsing (Vázquez-Semadeni *et al.*, 2005b; Nakamura and Li, 2005).

Chemical methods rely on matching the observed chemistry in cores to evolutionary models (e.g., Taylor *et al.*, 1996; 1998; Morata *et al.*, 2005). They suggest that not all cores will proceed to form stars. Langer *et al.* (2000) summarize comparisons of observed molecular abundances to time-dependent chemical models suggesting typical ages for cores of  $\sim 10^5$  yr. Using a similar technique, Jørgensen *et al.* (2005) report a timescale of  $10^{5 \pm 0.5}$  yr for the heavy-depletion, dense prestellar stage.

These timescales have been claimed to pose a problem for the model of AD-mediated, quasi-static, core contraction (Lee and Myers, 1999; Jijina *et al.*, 1999), as they amount to only a few local free-fall times ( $t_{\text{ff}} \equiv L_{\text{J}}/c_{\text{s}}$ ,  $\sim 0.5$  Myr for typical cores with  $\langle n \rangle \sim 5 \times 10^4 \text{ cm}^{-3}$ , where  $L_{\text{J}}$  is the local Jeans length, and  $c_{\text{s}}$  is the sound speed), rather than the 10–20  $t_{\text{ff}}$  predicted by the theory of AD-controlled star formation under the assumption of low initial values ( $\sim 0.25$ ) of the mass-to-magnetic flux ratio (in units of the critical value)  $\mu_0$  (e.g., Ciolek and Mouschovias, 1995). However, Ciolek and Basu (2001) have pointed out that the lifetimes of the ammonia-observable cores predicted by the AD theory are much lower, reaching values as small as  $\sim 2t_{\text{ff}}$  when  $\mu_0 \sim 0.8$ . Moreover, nonlinear effects can enhance the AD rates over the linear estimates (Fatuzzo and Adams, 2002; Heitsch *et al.*, 2004).

The lifetimes and evolution of dense cores have recently been investigated numerically by two groups. Vázquez-Semadeni *et al.* (2005b) and Vázquez-Semadeni *et al.* (2005a) considered driven, ideal MHD, magnetically supercritical turbulence with sustained rms Mach number  $\mathcal{M} \sim 10$ , comparable to Taurus, while Nakamura and Li (2005) considered subcritical, decaying turbulence including AD, in which the flow spent most of the time at low  $\mathcal{M}$ ,  $\sim 2$ –3. Thus, the two setups probably bracket the conditions in actual MCs. Nevertheless, the lifetimes found in both studies agree within a factor  $\sim 1.5$ , ranging from 0.5–10 Myr, with a median value  $\sim 2$ –3  $t_{\text{ff}}$  ( $\sim 1$ –1.5 Myr), with the longer timescales corresponding to the decaying cases. Furthermore, a substantial fraction of quiescent, trans- or subsonic cores, and low star formation efficiencies were found (Klessen *et al.* 2005; see also Section 4.2), comparable to those observed in the Taurus molecular cloud (TMC). In all cases, the simulations reported a substantial fraction of re-expanding (“failed”) cores.

This suggests that the AD timescale, when taking into account the nearly magnetically-critical nature of the clouds as well as nonlinear effects and turbulence-accelerated core formation, is comparable to the dynamical timescale. The notion of quasi-static, long-lived cores as the general rule is therefore unfounded, except in cases where a warm confining medium is clearly available (B68 may be an example; Alves *et al.*, 2001). Both observational and numerical evidence point towards short typical core lifetimes of a few  $t_{\text{ff}}$ , or a few hundred thousand to a million years, although the scatter around these values can be large.



## 4.2. Core structure

**4.2.1. Morphology and magnetic field.** MC cores in general, and starless cores in particular, have a median projected aspect ratio  $\sim 1.5$  (e.g., *Jijina et al.*, 1999, and references therein). It is not clear whether the observed aspect ratios imply that MC cores are (nearly) oblate or prolate. *Myers et al.* (1991) and *Ryden* (1996) found that cores are more likely to be prolate than oblate, while *Jones et al.* (2001) found them to be more likely oblate, as favored by AD-mediated collapse. MHD numerical simulations of turbulent MCs agree with generally triaxial shapes, with a slight preference for prolateness (*Gammie et al.*, 2003; *Li et al.*, 2004).

The importance of magnetic fields to the morphology and structure of MCs remains controversial. Observationally, although some cores exhibit alignment (e.g., *Wolf et al.*, 2003), it is common to find misalignments between the polarization angles and the minor axis of MC cores (e.g., *Heiles et al.*, 1993; *Ward-Thompson et al.*, 2000; *Crutcher et al.*, 2004). On the other hand, in modern models of AD-controlled contraction, triaxial distributions may exist, but the cores are expected to still be intrinsically flattened along the field (*Basu*, 2000; *Jones et al.*, 2001; *Basu and Ciolek*, 2004). However, numerical simulations of turbulent magnetized clouds tend to produce cores with little or no alignment with the magnetic field and a broad distribution of shapes (*Ballesteros-Paredes and Mac Low*, 2002; *Gammie et al.*, 2003; *Li et al.*, 2004).

Finally, a number of theoretical and observational works have studied the polarized emission of dust from MC cores. Their main conclusions are (a) cores in magnetized simulations exhibit degrees of polarization between 1 and 10%, regardless of whether the turbulence is sub- or super-Alfvénic (*Padoan et al.*, 2001a); (b) submillimeter polarization maps of quiescent cores do not map the magnetic fields inside the cores for visual extinctions larger than  $A_V \sim 3$  (*Padoan et al.*, 2001a), in agreement with observations (e.g., *Ward-Thompson et al.*, 2000; *Wolf et al.*, 2003; *Crutcher et al.*, 2004; *Bourke and Goodman*, 2004); (c) although the simplest Chandrasekhar-Fermi method of estimating the mean magnetic field in a turbulent medium underestimates very weak magnetic fields by as much as a factor of 150, it can be readily modified to yield estimates good to a factor of 2.5 for all field strengths (*Heitsch et al.*, 2001b); and (d) limited telescope resolution leads to a systematic overestimation of field strength, as well as to an impression of more regular, structureless magnetic fields (*Heitsch et al.*, 2001b).

**4.2.2. Density and Velocity Fields.** Low-mass MC cores often exhibit column density profiles resembling those of Bonnor-Ebert spheres (e.g., *Alves et al.* 2001; see also the chapter by *Lada et al.*), and trans- or even subsonic non-thermal linewidths (e.g., *Jijina et al.* 1999; *Tafalla et al.* 2004; see also the chapter by *di Francesco et al.*). These results have been traditionally interpreted as evidence that MC cores are in quasi-static equilibrium, and are therefore

long-lived. This is in apparent contradiction with the discussion from Section 4.1 (see, e.g., the discussion in *Keto and Field*, 2006), which presented evidence favoring the view that cores are formed by supersonic compressions in MCs, and that their lifetimes are of the order of one dynamical timescale. It is thus necessary to understand how those observational properties are arrived at, and whether dynamically-evolving cores reproduce them.

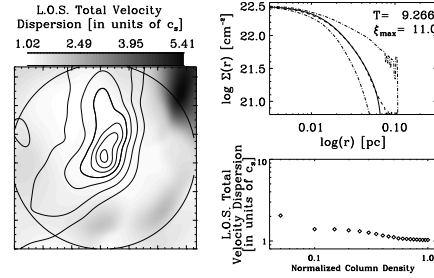


Fig. 2.— Properties of a typical quiescent core formed by turbulence in non-magnetic simulations of molecular clouds. *Left*: Column-density contours on the projected plane of the sky, superimposed on a grey-scale image of the *total* (thermal plus non-thermal) velocity dispersion along each line of sight, showing that the velocity dispersion occurs near the periphery of the core. *Upper-right*: A fit of a Bonnor-Ebert profile to the angle-averaged column density radial profile (*solid line*) within the circle on the map. The *dash-dotted* lines give the range of variation of individual radial profiles before averaging. *Lower right*: Plot of averaged *total* velocity dispersion versus column density, showing that the core is subsonic. (Adapted from *Ballesteros-Paredes et al.* 2003 and *Klessen et al.* 2005).

Radial column density profiles of MC cores are obtained by averaging the actual three-dimensional structure of the density field twice: first, along the line of sight during the observation itself, and second, during the angle-averaging (*Ballesteros-Paredes et al.*, 2003). These authors (see also Fig. 2) further showed that non-magnetic numerical simulations of turbulent MCs may form rapidly-evolving cores that nevertheless exhibit Bonnor-Ebert-like angle-averaged column density profiles, even though they are formed by a supersonic turbulent compression and are transient structures. Furthermore, *Klessen et al.* (2005) have shown that  $\sim 1/4$  of the cores in their simulations have subsonic internal velocity dispersions, while  $\sim 1/2$  of them are transonic, with velocity dispersions  $c_s < \sigma_{\text{turb}} \leq 2c_s$ , where  $c_s$  is the sound speed (Fig. 2). These fractions are intermediate between those reported by *Jijina et al.* (1999) for the Taurus and the Perseus MCs. These authors also showed that the ratio of virial to actual core masses in simulations with large-scale driving (LSD, 1/2 the simulation size) is reasonably consistent with observations, while that in simulations with small-scale driving (SSD) is not (Fig. 3), in agreement with the discussion in Section 3.2. Improved agreement with observations may be expected for models spanning a larger range of cloud masses.

Quiescent cores in turbulence simulations are not a con-



sequence of (quasi)-hydrostatic equilibrium, but a natural consequence of the  $\Delta v$ - $R$  relation, which implies that the typical velocity differences across small enough regions ( $l_s \lesssim 0.05$  pc) are subsonic, with  $\sigma_{\text{turb}} \lesssim c_s$ . Thus, it can be expected that small cores within turbulent environments may have trans- or even subsonic non-thermal linewidths. Moreover, the cores are assembled by random ram-pressure compressions in the large-scale flow, and as they are compressed, they trade kinetic compressive energy for internal energy, so that when the compression is at its maximum, the velocity is at its minimum (Klessen *et al.*, 2005). Thus, the observed properties of quiescent low-mass protostellar cores in MCs do not necessarily imply the existence of strong magnetic fields providing support against collapse nor of nearly hydrostatic states.

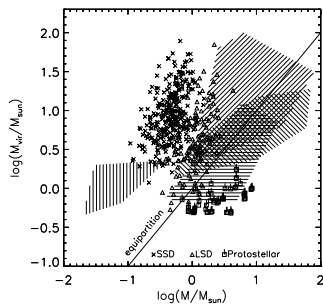


Fig. 3.— Virial mass  $M_{\text{vir}}$  vs. actual mass  $M$  for cores in turbulent models driven at small scales (crosses; “SSD”) and at large scales (triangles; “LSD”). Tailed squares indicate lower limits on the estimates on  $M_{\text{vir}}$  for cores in the LSD model containing “protostellar objects” (sink particles). The solid line denotes the identity  $M_{\text{vir}} = M$ . Also shown are core survey data by Morata *et al.* (2005, vertical hatching), Onishi *et al.* (2002, horizontal hatching), Caselli *et al.* (2002,  $-45^\circ$  hatching), and Tachihara *et al.* (2002,  $+45^\circ$  hatching). From Klessen *et al.* (2005).

**4.2.3. Energy and Virial Budget.** The notion that MCs and their cores are in near virial equilibrium is almost universally encountered in the literature (e.g., Larson, 1981; Myers and Goodman, 1988; McKee, 1999; Krumholz *et al.*, 2005a, and references therein). However, what is actually observed is energy equipartition between self-gravity and one or more forms of their internal energy, as Myers and Goodman (1988), for example, explicitly recognize. This by no means implies equilibrium, as the full virial theorem also contains hard to observe surface and time derivative terms (Spitzer, 1968; Parker, 1979; McKee and Zweibel, 1992). Even the energy estimates suffer from important observational uncertainties (e.g., Blitz, 1994). On the other hand, a core driven into gravitational collapse by an external compression naturally has an increasing ratio of its gravitational to the kinetic plus magnetic energies, and passes through equipartition at the verge of collapse, even if the process is fully dynamic. This is consistent with the observational fact that in general, a substantial fraction of clumps in MCs are gravitationally unbound (Maloney, 1990; Fal-

garone *et al.*, 1992; Bertoldi and McKee, 1992), a trend also observed in numerical simulations (Vázquez-Semadeni *et al.*, 1997).

Indeed, in numerical simulations of the turbulent ISM, the cores formed as turbulent density enhancements are continually changing their shapes, and exchanging mass, momentum and energy with their surroundings, giving large values of the surface and time derivative terms in the virial theorem (Ballesteros-Paredes and Vázquez-Semadeni 1995; 1997; Tilley and Pudritz 2004; see Ballesteros-Paredes 2004 for a review). That the surface terms are large indicates that there are fluxes of mass, momentum and energy across cloud boundaries. Thus, we conclude that observations of equipartition do not necessarily support the notion of equilibrium, and that a dynamical picture is consistent with the observations.

## 5. CONTROL OF STAR FORMATION

### 5.1. Star Formation Efficiency as Function of Turbulence Parameters

The fraction of molecular gas mass converted into stars, called the star formation efficiency (SFE), is known to be small, ranging from a few percent for entire MC complexes (e.g., Myers *et al.*, 1986) to 10–30% for cluster-forming cores (e.g., Lada and Lada, 2003) and 30% for starburst galaxies whose gas is primarily molecular (Kennicutt, 1998). Li *et al.* (2006) suggest that large-scale gravitational instabilities in galaxies may directly determine the global SFE in galaxies. They find a well-defined, nonlinear relationship between the gravitational instability parameter  $Q_{\text{sg}}$  (see Section 2.1) and the SFE.

Stellar feedback reduces the SFE in MCs both by destroying them, and by driving turbulence within them (e.g., Franco *et al.*, 1994; Williams and McKee, 1997; Matzner and McKee, 2000; Matzner, 2001; 2002; Nakamura and Li, 2005). Supersonic turbulence has two countervailing effects that must be accounted for. If it has energy comparable to the gravitational energy, it disrupts monolithic collapse, and if driven can prevent large-scale collapse. However, these same motions produce strong density enhancements that can collapse locally, but only involve a small fraction of the total mass. Its net effect is to delay collapse compared to the same situation without turbulence (Vázquez-Semadeni and Passot, 1999; Mac Low and Klessen, 2004). The magnetic field is only an additional contribution to the support, rather than the fundamental mechanism regulating the SFE.

As discussed in Section 3, the existence of a scaling relation between the velocity dispersion and the size of a cloud or clump implies that within structures sizes smaller than the sonic scale  $\lambda_s \sim 0.05$  pc turbulence is subsonic. Within structures with scale  $\ell > \lambda_s$ , turbulence drives subfragmentation and prevents monolithic collapse hierarchically (smaller fragments form within larger ones), while on scales  $\ell < \lambda_s$  turbulence ceases to be a dominant form of support, and cannot drive further subfragmentation (Padoan,

1995; Vázquez-Semadeni et al., 2003). (Subsonic turbulence, however, can still produce weakly nonlinear density fluctuations that can act as seeds for gravitational fragmentation of the core during its collapse; Goodwin et al. 2004a) Cores with  $\ell < \lambda_s$  collapse if gravity overwhelms their thermal and magnetic pressures, perhaps helped by ram pressure acting across their boundaries (Hunter and Fleck, 1982).

Numerical simulations neglecting magnetic fields showed that the SFE decreases monotonically with increasing turbulent energy or with decreasing energy injection scale (Léorat et al., 1990; Klessen et al., 2000; Clark and Bonnell, 2004). A remarkable fact is that the SFE was larger than zero even for simulations in which the turbulent Jeans mass (the Jeans mass including the turbulent RMS velocity; Chandrasekhar, 1951) was larger than the simulation mass, showing that turbulence can induce local collapse even in globally unbound clouds (Vázquez-Semadeni et al., 1996; Klessen et al., 2000; Clark and Bonnell, 2004; Clark et al., 2005).

A correlation between the SFE and  $\lambda_s$ ,  $\text{SFE}(\lambda_s) = \exp(-\lambda_0/\lambda_s)$ , with  $\lambda_0 \sim 0.05$  pc, was found in the numerical simulations of Vázquez-Semadeni et al. (2003). This result provided support to the idea that the sonic scale helps determine the SFE. Krumholz and McKee (2005) have further suggested that the other crucial parameter is the Jeans length  $L_J$ , and computed, from the probability distribution of the gas density, the fraction of the gas mass that has  $L_J \lesssim \lambda_s$ , which then gives the star formation rate per free-fall time. A recent observational study by Heyer et al. (2006) only finds a correlation between the sonic scale and the SFE for a subset of clouds with particularly high SFE, while no correlation is observed in general. This result might be a consequence of Heyer et al. (2006) not taking into account the clouds' Jeans lengths, as required by Krumholz and McKee (2005).

The influence of magnetic fields in controlling the SFE is a central question in the turbulent model, given their fundamental role in the AD-mediated model. Numerical studies using ideal MHD, neglecting AD, have shown that the field can only prevent gravitational collapse if it provides *magnetostatic* support, while MHD waves can only delay the collapse, but not prevent it (Ostriker et al., 1999; Heitsch et al., 2001a; Li et al., 2004). Vázquez-Semadeni et al. (2005a) found a trend of decreasing SFE with increasing mean field strength in *driven* simulations ranging from non-magnetic to moderately magnetically supercritical. In addition, a trend to form fewer but more massive objects in more strongly magnetized cases was also observed (see Fig. 4). Whole-cloud efficiencies  $\lesssim 5\%$  were obtained for moderately supercritical regimes at Mach numbers  $\mathcal{M} \sim 10$ . For comparison, Nakamura and Li (2005) found that comparable efficiencies in decaying simulations at *effective* Mach numbers  $\mathcal{M} \sim 2-3$  required moderately subcritical clouds in the presence of AD. These results suggest that whether MC turbulence is driven or decaying is a crucial question for quantifying the role of the magnetic field in limiting the

SFE in turbulent MCs.

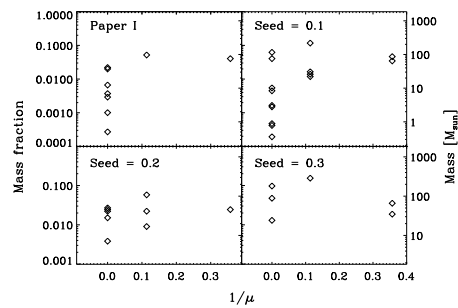


Fig. 4.— Masses of the collapsed objects formed in four sets of simulations with rms Mach number  $\mathcal{M} \sim 10$  and 64 Jeans masses. Each set contains one non-magnetic run and two MHD runs each. The latter with have initial mass-to-flux ratio  $\mu_0 = 8.8$  and  $\mu_0 = 2.8$ , showing that the magnetic runs tend to form fewer but more massive objects (From Vázquez-Semadeni et al. 2005a).

The relationship between the global and local SFE in galaxies still needs to be elucidated. The existence of the Kennicutt-Schmidt law shows that global SFEs vary as a function of galactic properties, but there is little indication that the local SFE in individual MCs varies strongly from galaxy to galaxy. Are they in fact independent?

## 5.2. Distribution of Clump Masses and Relation to the IMF

The stellar IMF is a fundamental diagnostic of the star formation process, and understanding its physical origin is one of the main goals of any star formation theory. Recently, the possibility that the IMF is a direct consequence of the protostellar core mass distribution (CMD) has gained considerable attention. Observers of dense cores report that the slope at the high-mass end of the CMD resembles the Salpeter (1955) slope of the IMF (e.g., Motte et al., 1998; Testi and Sargent, 1998). This has been interpreted as evidence that those cores are the direct progenitors of single stars.

Padoan and Nordlund (2002) computed the mass spectrum of self-gravitating density fluctuations produced by isothermal supersonic turbulence with a log-normal density PDF and a power-law turbulent energy spectrum with slope  $n$ , and proposed to identify this with the IMF. In this theory, the predicted slope of the IMF is given by  $-3/(4-n)$ . For  $n = 1.74$ , this gives  $-1.33$ , in agreement with the Salpeter IMF, although this value of  $n$  may not be universal (see Section 3.3). However, this theory suffers from a problem common to any approach that identifies the core mass function with the IMF: it implicitly assumes that the final stellar mass is proportional to the core mass, at least on average. Instead, high-mass cores have a larger probability to build up multiple stellar systems than low-mass ones.

Moreover, the number of physical processes that may play an important role during cloud fragmentation and protostellar collapse is large. In particular, simulations show

that (a) The mass distribution of cores changes with time as cores merge with each other (e.g., *Klessen*, 2001a). (b) Cores generally produce not a single star but several with the number stochastically dependent on the global parameters (e.g., *Klessen et al.*, 1998; *Bate and Bonnell*, 2005; *Dobbs et al.*, 2005), even for low levels of turbulence (*Goodwin et al.*, 2004b). (c) The shape of the clump mass spectrum appears to depend on parameters of the turbulent flow, such as the scale of energy injection (*Schmeja and Klessen*, 2004) and the rms Mach number of the flow (*Ballesteros-Paredes et al.*, 2006), perhaps because the density power spectrum of isothermal, turbulent flows becomes shallower when the Mach number increases (*Cho and Lazarian*, 2003; *Beresnyak et al.*, 2005; *Kim and Ryu*, 2005). Convergence of this result as numerical resolution increases sufficiently to resolve the turbulent inertial range needs to be confirmed. A physical explanation may be that stronger shocks produce denser, and thus thinner, density enhancements. Finally, there may be other processes like (d) competitive accretion influencing the mass-growth history of individual stars (see, e.g., *Bate and Bonnell* 2005, but for an opposing view *Krumholz et al.* 2005b), (e) stellar feedback through winds and outflows (e.g., *Shu et al.*, 1987), or (f) changes in the equation of state introducing preferred mass scales (e.g., *Scalo et al.*, 1998; *Li et al.*, 2003; *Jappsen et al.*, 2005; *Larson*, 2005). Furthermore, even though some observational and theoretical studies of dense, compact cores fit power-laws to the high-mass tail of the CMD, the actual shape of those CMDs is often not a single-slope power law, but rather a function with a continuously-varying slope, frequently similar to a log-normal distribution (*Ballesteros-Paredes et al.* 2006; see also Fig. 6 in the chapter by *Bonnell et al.*). So, the dynamic range in which a power-law with slope  $-1.3$  can be fitted is often smaller than one order of magnitude. All these facts call the existence of a simple one-to-one mapping between the purely turbulent clump-mass spectrum and the observed IMF into question.

Finally, it is important to mention that, although it is generally accepted that the IMF has a slope of  $-1.3$  at the high-mass range, the universal character of the IMF is still a debated issue, with strong arguments being given both in favor of a universal IMF (*Elmegreen*, 2000a; *Kroupa*, 2001; 2002; *Chabrier*, 2005) and against it in the Arches cluster (*Stolte et al.*, 2005), the Galactic Center region (*Nayakshin and Sunyaev*, 2005) and near the central black hole of M31 (*Bender et al.*, 2005).

We conclude that both the uniqueness of the IMF and the relationship between the IMF and the CMD are presently uncertain. The definition of core boundaries usually involves taking a density threshold. For a sufficiently high threshold, the CMD must reflect the IMF, while for lower thresholds subfragmentation is bound to occur. Thus, future studies may find it more appropriate to ask *at what density threshold* does a one-to-one relation between the IMF and the CMD finally occur.

### 5.3. Angular Momentum and Multiplicity

The specific angular momentum and the magnetic field of a collapsing core determines the multiplicity of the stellar system that it forms. We first review how core angular momentum is determined, and then how it in turn influences multiplicity.

**5.3.1. Core Angular Momentum.** Galactic differential rotation corresponds to a specific angular momentum  $j \approx 10^{23} \text{ cm}^2 \text{ s}^{-1}$ , while on scales of cloud cores, below 0.1 pc,  $j \approx 10^{21} \text{ cm}^2 \text{ s}^{-1}$ . A binary G star with an orbital period of 3 days has  $j \approx 10^{19} \text{ cm}^2 \text{ s}^{-1}$ , while the spin of a typical T Tauri star is a few  $\times 10^{17} \text{ cm}^2 \text{ s}^{-1}$ . Our own Sun rotates only with  $j \approx 10^{15} \text{ cm}^2 \text{ s}^{-1}$ . Angular momentum must be lost at all stages (for a review, see *Bodenheimer*, 1995).

Specific angular momentum has been measured in clumps and cores at various densities with different tracers: (a)  $n \sim 10^3 \text{ cm}^{-3}$  observed in  $^{13}\text{CO}$  (*Arquilla and Goldsmith*, 1986); (b)  $n \sim 10^4 \text{ cm}^{-3}$  observed in  $\text{NH}_3$  (e.g., *Goodman et al.* 1993; *Barranco and Goodman* 1998; see also *Jijina et al.* 1999); (c)  $n \sim 10^4 - 10^5 \text{ cm}^{-3}$  observed in  $\text{N}_2\text{H}^+$  in both low (*Caselli et al.*, 2002) and high (*Pirogov et al.*, 2003) mass star forming regions. In all these objects, the rotational energy is considerably lower than required for support; in the densest cores the difference is an order of magnitude. *Jappsen and Klessen* (2004) showed that these clumps form an evolutionary sequence with  $j$  declining with decreasing scale. Main sequence binaries have  $j$  just below that of the densest cores.

Magnetic braking has long been thought to be the primary mechanism for the redistribution of angular momentum out of collapsing objects (*Ebert et al.*, 1960; *Mouschovias and Paleologou*, 1979; 1980). Recent results suggest that magnetic braking may be less important than was thought. Two groups have now performed MHD models of self-gravitating, decaying (*Gammie et al.*, 2003) and driven (*Li et al.*, 2004) turbulence, finding distributions of specific angular momentum consistent with observed cores and with each other. Surprisingly, however, *Jappsen and Klessen* (2004) found similar results with *hydrodynamic* models (see also *Tilley and Pudritz*, 2004), suggesting that accretion and gravitational interactions may dominate over magnetic braking in determining how angular momentum is lost during the collapse of cores. *Fisher* (2004) reached similar conclusions based on semi-analytical models.

**5.3.2. Multiplicity.** Young stars frequently have a higher multiplicity than main sequence stars in the solar neighborhood (*Duchêne*, 1999; *Mathieu et al.*, 2000), suggesting that stars are born with high multiplicity, but binaries are then destroyed dynamically during their early lifetime (*Simon et al.*, 1993; *Kroupa*, 1995; *Patience et al.*, 1998). In addition, multiplicity depends on mass. Main sequence stars with lower masses have lower multiplicity (*Lada*, 2006).

Fragmentation during collapse is considered likely to be the dominant mode of binary formation (*Bodenheimer et al.*, 2000). Hydrodynamic models showed that isother-

mal spheres with a ratio of thermal to gravitational energy  $\alpha < 0.3$  fragment (Miyama *et al.*, 1984; Boss, 1993; Boss and Myhill, 1995; Tsuribe and Inutsuka, 1999b;a), and that even clumps with larger  $\alpha$  can still fragment if they rotate fast enough to form a disk (Matsumoto and Hanawa, 2003).

The presence of protostellar jets driven by magnetized accretion disks (e.g., Königl and Ruden, 1993) strongly suggests that magnetic braking must play a significant role in the final stages of collapse when multiplicity is determined. Low resolution MHD models showed strong braking and no fragmentation (Dorfi, 1982; Benz, 1984; Phillips, 1986a;b; Hosking and Whitworth, 2004). Boss (2000; 2001; 2002; 2005) found that fields enhanced fragmentation, but neglected magnetic braking by only treating the radial component of the magnetic tension force. Ziegler (2005) showed that field strengths small enough to allow for binary formation cannot provide support against collapse, offering additional support for a dynamic picture of star formation.

High resolution models using up to 17 levels of nested grids have now been done for a large number of cores Machida *et al.* (2005a;b). These clouds were initially cylindrical, in hydrostatic equilibrium, threaded by a magnetic field aligned with the rotation axis having uniform plasma  $\beta_p$  (the ratio of magnetic field to thermal pressure; Machida *et al.* 2004). At least for these initial conditions, fragmentation and binary formation happens during collapse if the initial ratio

$$\frac{\Omega_0}{B_0} > \frac{G^{1/2}}{2^{1/2}c_s} \sim 3 \times 10^7 \text{ yr}^{-1} \mu \text{ G}^{-1}. \quad (1)$$

Whether this important result generalizes to other geometries clearly needs to be confirmed.

If prestellar cores form by collapse and fragmentation in a turbulent flow, then nearby protostars might be expected to have aligned angular momentum vectors as seen in models (Jappsen and Klessen, 2004). This appears to be observed in binaries (Monin *et al.*, 2006), and stars with ages less than  $10^6$  yr. However, the effect fades with later ages (e.g., Ménard and Duchêne, 2004). Ménard and Duchêne (2004) also make the intriguing suggestion that jets may only appear if disks are aligned with the local magnetic field.

#### 5.4. Importance of Dynamical Interactions During Star Formation

Rich compact clusters can have large numbers of protostellar objects in small volumes. Thus, dynamical interactions between protostars may become important, introducing a further degree of stochasticity to the star formation process besides the statistical chaos associated with the gravoturbulent fragmentation process.

Numerical simulations have shown that when a MC region of a few hundred solar masses or more coherently becomes gravitationally unstable, it contracts and builds up a dense clump highly structured in a hierarchical way, containing compact protostellar cores (e.g., Klessen and Burkert, 2000; 2001; Bate *et al.*, 2003; Clark *et al.*, 2005). Those

cores may contain multiple collapsed objects that will compete with each other for further mass accretion in a common limited and rapidly changing reservoir of contracting gas. The relative importance of these competitive processes depends on the initial ratio between gravitational vs. turbulent and magnetic energies of the cluster-forming core (Krumholz *et al.* 2005b; see also the chapter by Bonnell *et al.*). If gravitational contraction strongly dominates the dynamical evolution, as seems probable for the formation of massive, bound clusters, then the following effects need to be considered.

(a) Dynamical interactions between collapsed objects during the embedded phase of a nascent stellar cluster evolve towards energy equipartition. As a consequence, massive objects will have, on average, smaller velocities than low-mass objects. They sink towards the cluster center, while low-mass stars predominantly populate large cluster radii. This effect already holds for the embedded phase (e.g., Bonnell and Davies, 1998; Klessen and Burkert, 2000; Bonnell *et al.*, 2004), and agrees with observations of young clusters (e.g., Sirianni *et al.*, 2002, for NGC330 in the Small Magellanic Cloud).

(b) The most massive cores within a large clump have the largest density contrast and collapse first. In there, the more massive protostars begin to form first and continue to accrete at a high rate throughout the entire cluster evolution ( $\sim 10^5$  yr). As their parental cores merge with others, more gas is fed into their ‘sphere of influence’. They are able to maintain or even increase the accretion rate when competing with lower-mass objects (e.g., Schmeja and Klessen, 2004; Bonnell *et al.*, 2004).

(c) The previous processes lead to highly time-variable protostellar mass growth rates (e.g., Bonnell *et al.*, 2001a; Klessen, 2001b; Schmeja and Klessen, 2004). As a consequence, the resulting stellar mass spectrum can be modified (Field and Saslaw 1965; Silk and Takahashi 1979; Lejeune and Bastien 1986; Murray and Lin 1996; Bonnell *et al.* 2001b; Klessen 2001a; Schmeja and Klessen 2004; Bate and Bonnell 2005; see also the chapters by Bonnell *et al.* and Whitworth *et al.*). Krumholz *et al.* (2005b) argue that these works typically do not resolve the Bondi-Hoyle radius well enough to derive quantitatively correct accretion rates, but the qualitative statement appears likely to remain correct.

(d) Stellar systems with more than two members are in general unstable, with the lowest-mass member having the highest probability of being expelled (e.g., van Albada, 1968).

(e) Although stellar collisions have been proposed as a mechanism for the formation of high-mass stars (Bonnell *et al.*, 1998; Stahler *et al.*, 2000), detailed 2D and 3D calculations (Yorke and Sonnhalter, 2002; Krumholz *et al.*, 2005a) show that mass can be accreted from a protostellar disk onto the star. Thus, collisional processes need not be invoked for the formation of high-mass stars (see also, Krumholz *et al.*, 2005b).

(f) Close encounters in nascent star clusters can trun-

cate and/or disrupt the accretion disk expected to surround (and feed) every protostar. This influences mass accretion through the disk, modifies the ability to subfragment and form a binary star, and the probability of planet formation (e.g., *Clarke and Pringle*, 1991; *McDonald and Clarke*, 1995; *Scally and Clarke*, 2001; *Kroupa and Burkert*, 2001; *Bonnell et al.*, 2001c). In particular, *Ida et al.* (2000) note that an early stellar encounter may explain features of our own solar system, namely the high eccentricities and inclinations observed in the outer part of the Edgeworth-Kuiper Belt at distances larger than 42 AU.

(g) While competitive coagulation and accretion is a viable mechanism in very massive and dense star-forming regions, protostellar cores in low-mass, low-density clouds such as Taurus or  $\rho$ -Ophiuchus are less likely to strongly interact with each other.

### 5.5. Effects of Ionization and Winds

When gravitational collapse proceeds to star formation, ionizing radiation begins to act on the surrounding MC. This can drive compressive motions that accelerate collapse in surrounding gas, or raise the energy of the gas sufficiently to dissociate molecular gas and even drive it out of the potential well of the cloud, ultimately destroying it. Protostellar outflows can have similar effects, but are less powerful, and probably do not dominate cloud energy (*Matzner* 2002; *Nakamura and Li* 2005; see also the chapter by *Arce et al.* 2006).

The idea that the expansion of H II regions can compress the surrounding gas sufficiently to trigger star formation was proposed by *Elmegreen and Lada* (1977). Observational and theoretical work supporting it was reviewed by *Elmegreen* (1998). Since then, it has become reasonably clear that star formation is more likely to occur close to already formed stars than elsewhere in a dark cloud (e.g., *Ogura et al.*, 2002; *Stanke et al.*, 2002; *Karr and Martin*, 2003; *Barbá et al.*, 2003; *Clark and Porter*, 2004; *Healy et al.*, 2004; *Deharveng et al.*, 2005). However, the question remains whether this seemingly triggered star formation would have occurred anyway in the absence of the trigger. Massive star formation occurs in gravitationally collapsing regions where low mass star formation is anyway abundant. The triggering shocks produced by the first massive stars may determine in detail the configuration of newly formed stars without necessarily changing the overall star formation efficiency of the region (*Elmegreen*, 2002; *Hester et al.*, 2004). Furthermore, the energy input by the shock fronts has the net effect of inhibiting collapse by driving turbulence (*Matzner*, 2002; *Vázquez-Semadeni et al.*, 2003; *Mac Low and Klessen*, 2004), even if it can not prevent local collapse (see Section 5.1).

The study of the dissociation of clouds by ionizing radiation also has a long history, stretching back to the 1D analytic models of *Whitworth* (1979) and *Bodenheimer et al.* (1979). The latter group first noted the champagne effect, in which ionized gas in a density gradient can blow out to-

ward vacuum at supersonic velocities. This mechanism was also invoked by *Blitz and Shu* (1980), and further studied by *Franco et al.* (1994) and *Williams and McKee* (1997). *Matzner* (2002) has performed a detailed analytic study recently, which suggests that the energy injected by H II regions is sufficient to support GMCs for as long as  $2 \times 10^7$  yr. One major uncertainty remaining is whether expanding H II regions can couple to the clumpy, turbulent gas as well as is assumed.

## 6. CONCLUSIONS

We have reviewed recent work on MC turbulence and discussed its implications for our understanding of star formation. There are several aspects of MC and star formation where our understanding of the underlying physical processes has developed considerably, but there are also a fair number of questions that remain unanswered. The following gives a brief overview.

(a) MCs appear to be transient objects, representing the brief molecular phase during the evolution of dense regions formed by compressions in the diffuse gas, rather than long-lived, equilibrium structures.

(b) Several competing mechanisms for MC formation remain viable. At the largest scales, the gravitational instability of the combined system of stars plus gas drives the formation of spiral density waves in which GMCs can form either by direct gravitational instability of the diffuse gas (in gas-rich systems), or by compression in the stellar potential followed by cooling (in gas poor systems). At smaller scales, supersonic flows driven by the ensemble of SN explosions have a similar effect.

(c) Similar times ( $< 10 - 15$  Myr) are needed both to assemble enough gas for a MC and to form molecules in it. This is less than earlier estimates. Turbulence-triggered thermal instability can further produce denser ( $10^3 \text{ cm}^{-3}$ ), compact H I clouds, where the production of molecular gas takes  $\lesssim 1$  Myr. Turbulent flow through the dense regions results in broad regions of molecular gas at lower average densities of  $\sim 100 \text{ cm}^{-3}$ .

(d) Interstellar turbulence seems to be driven from scales substantially larger than MCs. Internal MC turbulence may well be a byproduct of the cloud formation mechanism itself, explaining why turbulence is ubiquitously observed on all scales.

(e) MC cloud turbulence appears to produce a well-defined velocity-dispersion to size relation at the level of entire MC complexes, with an index  $\sim 0.5-0.6$ , but becoming less well defined as smaller objects are considered. The apparent density-size relation, on the other hand, is probably an observational artifact.

(f) MC cores are produced by turbulent compression and may, or may not, undergo gravitational instability. They evolve dynamically on timescales of  $\sim 10^6$  yr, but still can mimic certain observational properties of quastatic objects, such as sub- or transonic non-thermal central linewidth, or Bonnor-Ebert density profiles. These re-

sults agree with cloud statistics of nearby, well-studied regions.

(g) Magnetic fields appear unlikely to be of qualitative importance in structuring MC cores, although they probably do make a quantitative difference.

(h) Comparison of magnetized and unmagnetized simulations of self-gravitating, turbulent gas reveals similar angular momentum distributions. The angular momentum distribution of MC cores and protostars may be determined by turbulent accretion rather than magnetic braking.

(i) The interplay between supersonic turbulence and gravity on Galactic scales can explain the global efficiency of converting warm atomic gas into cold molecular clouds. The local efficiency of conversion of MCs into stars, on the other hand, seems to depend primarily on stellar feedback evaporating and dispersing the cloud, and only secondarily on the presence of magnetic fields.

(j) There are multiple reasons to doubt the existence of a simple one-to-one mapping between the purely turbulent clump mass spectrum and the observed IMF, despite observations showing that the dense self-gravitating core mass spectrum may resemble the IMF. A comprehensive understanding of the physical origin of the IMF remains elusive.

(k) In dense clusters, star formation might be affected by dynamical interactions. Close encounters between newborn stars and protostellar cores have the potential to modify their accretion history, and consequently the final stellar mass, as well as the size of protostellar disks, and possibly their ability to form planets and planetary systems.

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